UCRL- 89362
PREPRINT

THE MOTION CONTROL SYSTEM FOR THE LARGE OPTICS DIAMOND TURNING MACHINE (LODTM)

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This paper was prepared for submittal to
SPIE's 27th Annual International
Technical Symposium and Instrument Display

August 21-26, 1983

Lawrence Livermore National Laboratory

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Abstract

LODTM, built by LLNL for DOD, is a precision vertical lathe used to diamond turn large optical parts (to 64" diameter) to 1 µinch rms figure error. The LODTM motion controls require precision sensors, precision servos, and a wideband (330 Hz) real time computer. Position is sensed to 1/40 µinch resolution by laser interferometers and differential capacitance gauges. Precision servos operating at 1/10 µinch resolution and at low velocities with zero backlash are required. A unique Fast Tool Servo (FTS), located close to the diamond tool, adjusts the final tool position. The LODTM controls coordinate the X, Z, and FTS servos to cause the tool to move on a specified contour and at a specified feedrate in the X-Z plane. The part floppy diskette commands this motion with a linear CNC and real time (32-bit) computer. During each 1.5 ms sample time, the computer must DMA 14 sensor readings into memory, calculate the X and Z Tool Coordinates, calculate the FTS input, output the following errors, output the FTS input, store "flight recorder" information, and check for anomalies.

Introduction

Lawrence Livermore National Laboratory (LLNL) has built a precision vertical lathe to diamond turn large optics parts for the Defense Advanced Research Projects Agency (DARPA). The work was under the direction of the Air Force Wright Aeronautical Laboratory. This machine tool is designated the Large Optics Diamond Turning Machine (LODTM). LODTM will machine complex optical surfaces to within 1.0 µinch rms figure error while providing mirror-like finishes. The LODTM Motion Control System moves the tool in the X-Z plane over a prescribed contour and at a prescribed velocity with respect to the spinning spindle faceplate. By design, LODTM accommodates fixturing and parts of up to 64 inches in diameter, 20 inches in height, and 3000 lbs. (1360 kg) in weight. The design goal for tolerance is 1.1 µinch radial figure, 0.5 µinch azimuthal figure (excluding fixturing), and 0.17 µinch (42 Å) surface finish. During the final machine cut, the diamond tool will remove approximately 25 µinches of material.

Figure 1 shows an artist's concept of the Large Optics Diamond Turning Machine. LODTM has two structural frames. One is loaded by the carriage and tool bar assemblies; the other, the metrology frame, is unloaded and used for a measurement reference. Tool position is calculated based upon seven laser interferometer measurements, five differential capacitance gauges, and one spindle encoder. The first twelve of these sensors use the metrology frame as a reference. LODTM controls the temperature of the metrology frame to within a millidegree Celcius. A liquid coolant flows around the LODTM metrology frame to minimize temperature expansion length changes; this coolant is regulated to within ± 0.5 m°C. Figure 1 also shows the pneumatic isolation mounts used to isolate high frequency floor motion from the workpiece. Airborne acoustic noise is controlled by soundproofing and minimization of acoustic noise sources.

The "slide" servos (X and Z axes) and Fast Tool Servo (FTS) provide the means to move the diamond tool. The carriage moves the tool in the X direction while the tool bar moves the tool in the Z direction. Maximum X-axis travel is 40 inches and maximum Z-axis travel is 20 inches. A capstan rotary-to-linear motion assembly, powered by a dc torque motor with tachometer feedback, drives both the X and Z axes. In addition to the orthogonal X and Z slide motion, LODTM incorporates another axis of motion (FTS) within the X-Z plane. The Fast Tool Servo is required to follow the higher frequency (under 100 Hz), small amplitude (under ± 10 µinches) spindle motion. The FTS moves the diamond tool at a fixed angle within the X-Z plane and has a total travel of ± 50 µinches. The inputs to the X and Z axes slide drives plus the FTS are determined and coordinated by the Computer Numerical Controller (CNC) and the Real Time Computer (RTC).

Control System Concepts

The LODTM motion control system coordinates the three axes of motion so as to move the diamond tool on a specified path and at a specified velocity in the X-Z plane. The path and velocity are measured with respect to the spindle faceplate coordinate system (i.e., part being machined). Three modes of operation are possible: machining, measuring, and rapid traverse. These modes are chiefly characterized by their maximum velocities, which are:

Mode	Maximum Velocity in mil/sec	(µm/sec)
Machining	1	(25.4)
Measuring	10	(254)
Rapid Traverse	100	(2540)

The required positioning accuracy varies for the three modes. During machining, LODTM requires the most accurate positioning. Any tool position error in the X-Z plane directly becomes a part error. In the measurement mode, the diamond tool is replaced by a noncontacting position sensor. This sensor measures the small distance (approximately 100 μinches) between the part surface and the noncontacting sensor. The part surface position is the algebraic sum of the noncontacting sensor position (formerly, the tool position) and the measured distance between the sensor and surface. As long as the position of the sensor can be accurately determined and the noncontacting sensor does not hit the part surface, a much larger control system positioning error can be tolerated. During measuring, the tool bar position sensors and RTC calculations must be accurate, but the control system, as a loop, can have a much larger following error. While in the rapid traverse mode, the major requirements are that the tool velocity not exceed 0.1 inch/sec and that the tool not hit the part surface or LODTM structure. The tool position errors can have dynamic values of up to 0.1 inch provided that when velocities decrease to measuring or machining velocities, the position errors revert to appropriate values.

To control the diamond tool, LODTM uses three axes of motion: X (Carriage), Z (tool bar), and FTS (Piezoelectric Servo). The angle of the FTS motion in the X-Z plane is fixed for a given part. Figure 2 illustrates the functional LODTM control system block diagram. The Computer Numerical Controller (CNC) acts as an X and Z signal generator to the Real Time Computer (RTC); the X and Z set points are in a 32-bit, two's complement form. The RTC accepts the X and Z inputs (parallel I/O) and thirteen position sensor inputs (DMA). Based on the seven laser interferometer position sensors, five differential capacitance gauges, and one spindle encoder, the RTC computes the tool (X,Z) position coordinates with respect to the spindle faceplate. The axes following errors are calculated by subtracting the feedback tool position from the CNC input. The following errors drive the slide servos through the D/As. In addition to the following error calculations, the RTC computes the FTS input based on the axes following errors and parts slope. The tool position, following error, and FTS input calculations are updated every 1.5 milliseconds. The major component of the RTC is a 32-bit Perkin-Elmer 3220 computer with double precision (64-bit) floating point hardware.

The slide servos consist of a capstan rotary-to-linear motion drive, dc torque motor, dc tachometer, servo amplifier, and compensation electronics. Since the slide servos must move the tool bar and carriage masses and since these masses are coupled to the LODTM structural resonances, the slide servo bandwidth cannot easily be extended above the 20-30 Hertz range. Unfortunately, LODTM must account for small (<10 μinches) spindle motions with frequency components above 30 Hertz but below 100 Hertz. The Fast Tool Servo (FTS) allows the tool to follow small (± 50 μinches) motions to 100 Hertz. The FTS consists of a piezoelectric pusher, differential capacitance gauge, high voltage amplifier, and associated electronics. Based on the Nyquist Sampling Theorem and engineering practice, the highest frequency component of the spindle motion sets the sample data rate at 660 kHz. This ensures the FTS input faithfully reproduces signals below 100 Hertz. The servo motions cause the tool position to change. Position changes are measured by the thirteen sensors, read into the RTC, and a new tool feedback position is calculated. In this manner, the X and Z slide servo loops are closed. The use of the FTS does not introduce any additional stability problems since the FTS does not have a feedback path to the slide servos, and hence, axes following errors. The Fast Tool Servo feeds forward the slide servo following errors to correct the tool position (i.e., puts the tool on the tangent plane of the part) without affecting the slide servo following errors.

Precision Position Measurement

LODTM uses two types of precision sensors to measure tool position. These are laser interferometers and differential capacitance gauges. The LODTM laser interferometer system is based on two optical frequencies separated by 1.75 MHz and polarized orthogonally to each other. The LODTM system requires a laser stability of at least 1 part in 10^9 and electronics resolution extension of 256. The differential capacitance gauges used to measure spindle and tool bar motion are based on the work of Gabor [Ref. 1]. For a 100 Hertz sensor bandwidth with ± 100 μinches span, the LODTM differential capacitance gauge has 0.01 μinch analog peak-to-peak noise. For each of the sensors, custom electronics was developed. Each sensor used for tool position has a resolution of 1/40 μinch per least significant bit. The Fast Tool Servo uses a differential capacitance gauge with a 1/10 μinch resolution. As points of reference, 1/40 μinch is approximately 1/1024 the wavelength of red light and 1/200 μinch is approximately the spacing between atoms in aluminum. The advantage of the differential capacitance gauge is its compactness, ease of packaging, and relatively simple electronics. The advantage of the laser interferometer is its relatively long span (40 inches versus ± 100 μinches).

Analog Servos

LODTM uses two types of analog servos: the X and Z axes slide servos and the Fast Tool Servo. Table 1 summarizes the major closed loop servo characteristics. The two types of servos differ in span (40 inches for X, 20 inches for Z, versus ± 100 μinches for FTS), bandwidth (18.5 and 29.5 Hz for X and Z versus 640 Hz for FTS), and type (essentially Type 1 for X and Z versus Type 0 for FTS). Suppose the tool is commanded to move with a velocity of 1 mil/sec in the X direction. Since the X slide servo is essentially Type 1 with a velocity error coefficient of 5,200, the steady state following error is 0.2 μinch. As is later discussed, the RTC takes the slide following errors and computes the distance the FTS must move to keep the tool on the tangent plane. For steady state operation, the input to the FTS is a constant of approximately 0.2 μinch (the exact value is a function of the angle of the FTS and the angle of the tangent plane). Since the Fast Tool Servo is a Type 0 with a dc loop gain of 0.5×10^6, the FTS following error is approximately 0.4×10^{-6} μinches.

The capstan drive used in LODTM directly contacts the tool bar without the aid of gears. As the capstan rotates, it rolls the tool bar under itself. This rotary-to-linear motion conversion virtually eliminates drive backlash. The dc torque motor directly powers, through the common shaft, the capstan drive and tachometer. The frequencies and magnitude of the structural resonances that couple into the tachometer loop, in effect, determine the largest closed loop bandwidth possible. LODTM desires the widest obtainable closed loop tachometer bandwidth in order to maximize the frequency range over which good output disturbance rejection is realized, to minimize loop response time, to minimize phase shift in the position loop, and to maximize tachometer open loop gain (i.e., minimize effect of motor/tachometer nonlinearity). Figure 3 illustrates the Z slide axes. Note that the vacuum counterbalance works in parallel with the torque motor. This introduces a pair of complex zeros in the feedforward transfer function.

Since the capstan radius is 1 inch and since the maximum machining velocity is 1 mil/sec, the maximum motor angular velocity during machining is approximately 14 revolutions/day. Thus, low speed operation of the tachometer loop is important. A linear model predicts no low speed problems. In reality, motor tachometer nonlinearities complicate the low speed behavior. Figure 4 shows the dominant, low speed, nonlinearity measured in the servo test bed. When starting from standstill and for a small shaft angle (less than 50 μ radians), the dc torque motor/tachometer combination on an air bearing behaves as a spring [Ref. 2] with hysteresis. The effective spring constant is approximately 1 600 ft.-lb. radian. For angles larger than 50 μ radians, the torque appears as a constant drag. The mechanism thought responsible for the "spring" drag is the hysteresis torque due to the rotor taking a magnetic set. Because the nonlinearity is smooth and not coulomb in nature (i.e., continuous), ultra low speed operation of the tachometer loop is not impaired when tachometer loop gains are high. The servo test bed has obtained smooth operation down to 1/5 μinch per second in a position loop configuration. At this point, the servo was single stepping at one count equal to 0.1 μinch.

Figure 5 shows a mechanical cutaway of the Fast Tool Servo merged with a control block diagram. The FTS loop consists of a piezoelectric (PZT) pusher, differential capacitance gauge, high voltage driver, and analog compensation electronics. Since the PZT pusher has a high resonance frequency (approximately 1.2 kHz), the electronic compensation sets the 640 Hertz closed loop FTS bandwidth. The advantages of the FTS are: it can follow the high frequency spindle motion, it keeps the tool on the tangent plane, and it relaxes the slide servo positioning requirements.

The Real Time Computer calculates the FTS input based on the dynamic X and Z following errors and part slope. The tool position is the algebraic sum of the slide servo motion and FTS motion. The FTS moves the tool beyond a point on the tool bar which the slide servos sensors can "see"; thus, the slide servos cannot see the FTS motion. Except for reaction mass forces, the Fast Tool Servo displacements do not couple back into the X and Z slide servos. By design, reaction mass forces provide minimal cross-coupling feedback. Negative feedback minimizes the effects of PZT hysteresis by linearizing the driven element. As demonstrated by calculation and measurement, the dc loop gain adjusts the dc axial mechanical stiffness of the FTS. For the closed loop FTS, the calculated effective dc compliance of the mechanical components in the loop is 4×10^{-11} inches/lb.

In principle, a two axis (aligned with X and Z), stacked FTS is possible. The FTS inputs would then simply be the slide axis following errors. Unfortunately, the stacked FTS was not mechanically stiff enough in all directions for LODTM. LODTM's Fast Tool Servo used a single axis of motion to keep the diamond tool on the part tangent plane. Figure 6 illustrates the distance ℓ the tool must move. At any instance of time, the CNC commands a given X, Z coordinate. This is the desired position. The slide servos lag the actual command. This is the actual position. The difference between the desired and actual positions is the following error as shown in Figure 6. The distance from the actual position to the tangent plane along the FTS axis is the distance ℓ; this is the input to the FTS. Notice that in Figure 6 the diamond tool is displaced down the tangent plane a distance d. This displacement introduces a small error, ϵ, in the part. At the desired position, the part surface can be approximated by a radius of curvature R. For LODTM, R never falls below 0.1 inches and d is less than 1 μinch at maximum machining velocity. Therefore, ϵ is less than 10^{-11} inches and can be ignored.

Machine Control Unit

In Figure 2, the Machine Control Unit (MCU) consists of the Computer Numerical Controller (CNC) and Real Time Computer (RTC). Figure 7 illustrates in greater detail the interaction between the CNC and RTC. The LODTM MCU reads a part's description, provides the usual CNC control panel operations, outputs the X and Z slide following errors, generates the Fast Tool Servo input, provides for fault mode exception handling, and supplies the master clock.

The CNC reads the part's description from the "paper tape" floppy diskette. The interpolator converts this block of information into a sequence of 1.5 millisecond setpoints. These are the 32-bit integer X and Z position commands pictured in Figures 2 and 7. Notice that the slide position loop is closed within the RTC and not the CNC. LODTM will machine large optics parts characterized by radius of curvatures greater than 10 inches and smoothly varying surface contours. For this reason, linear interpolation is adequate for LODTM's CNC. The CNC setpoints (outputs) are specified to be within ± 0.5 count accuracy at all times. This output accuracy is difficult to ensure in circular interpolation due to numerical integration errors, but can be guaranteed in the linear interpolation mode. In addition to accuracy, the CNC requires 29 bits of position setpoint information to be available. The least significant bit (LSB) of the CNC setpoint equals 1/256 of the wavelength of red light, or approximately 0.1 μinches. The CNC has feedhold and emergency stop position limit switches plus emergency stop push buttons.

The Real Time Computer used for LODTM is the Perkin Elmer 3220. This machine has a 32-bit word size along with a hardware floating point unit. The tool position calculations are done using double precision (64-bit) floating point operations in FORTRAN. Table 2 lists the equations the RTC evaluates every 1.5 milliseconds. Note that the lookup tables require further indexing not shown in Table 2. Of the thirteen position sensors, seven contain 32-bit information and six contain 16-bit information. A custom sensor DMA channel was built to allow reading of the sensor information in under 100 μsec. Custom D/A and fault concentration hardware was also developed. Optical isolation separates the RTC from the CNC, sensor DMA channel, D/A outputs, and fault concentrator.

Figure 7 illustrates how the RTC interacts with the CNC, sensor DMA channel, analog servos, and fault concentrator. Under normal operation, the CNC alerts the RTC at the 1.5 millisecond sampling intervals. The X/Z setpoints and tangent plane information are read into the RTC. The part's tangent plane information is used in the FTS calculations. The RTC also reads the thirteen sensors via the DMA channel, calculates the X and Z tool position, forms the X and Z following errors, calculates the FTS input, and finally outputs the following errors and FTS input. From initiation to completion, the above cycle takes 1.2 milliseconds.

Machining time will be over 24 hours for some optical parts. Therefore, provisions must be made for system failures during machining. All fault signals external to the RTC are grouped together in the fault concentrator. Here, the first fault to arrive is separately noted and all faults that occur are displayed. Upon receiving a fault signal, the fault concentrator interrupts the Perkin-Elmer 3220. This external interrupt initiates the RTC safing sequence. The safing sequence can also be initiated by RTC self-checks. For example, the watchdog timer checks for excessive calculation time. Also, unusual calculations (out of bounds, rapid changes) can be flagged. Once the RTC safing sequence is initiated, the RTC commands the tool off the part, initiates an emergency stop, and stores the current tool position (and other information) for later recovery. For reliability reasons, the fault interrupt signal from the fault concentrator bypasses the RTC. The hardware emergency stop sequence, through hardware switching, will ensure that: the tool retracts from the part (removes power to PZT; PZT goes to the safe position), slide velocity is zero (input to servo amplifier set to zero and torque motor wires shorted), slide brakes are applied, and vacuum counterbalance bellows are sealed. If an emergency stop is issued by the machinist from the CNC control panel, rather than from the equipment, the RTC will note this fact by the connection to the fault concentrator.

Summary

A motion control system for precision positioning of the Large Optics Diamond Turning Machine has been implemented at LLNL for DOD. Surface contours are specified to the CNC on floppy diskette. The motion control system has a resolution of 0.1 μinch and a slide servo bandwidth of 18.5 Hertz. The Fast Tool Servo, for small motions, effectively extends the system bandwidth to a theoretical 330 Hertz.

Acknowledgements

Though many people have contributed to the information presented in this paper, the author would like to specifically acknowledge the following individuals: Steve Patterson, for his assistance in all areas of the LODTM Motion Control System; Al Maddux, for his contributions in theoretical and experimental work on servos and capacitance gauges; Tim Voss and Joe King, for their guidance in the digital portion of the LODTM motion control system; Tom Barich, for his work on the laser extension electronics and temperature sensing; Gordon North, for his work on the spindle drive; and Dave Hopkins, for his assistance in the digital portion of the LODTM controls, slide servos, FTS, and liquid temperature control.

References

1.) Position Sensors and Actuators for Figure Control of a Segmented Mirror Telescope, by George Gabor, Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720.

2.) Telephone conversation with Jack Kimbal, West Coast Representative of Inland Motors.

Auspices

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

TABLE 1: LODTM SERVO PERFORMANCE CHARACTERISTICS

LODTM Slide Servo Performance Characteristics

Position Loop	X-Axis		Z-Axis	
Actuator	Velocity Loop		Velocity Loop	
Position sensor	Interferometer		Interferometer	
Weight moved	4,000	lb	450	lb
Bearing type	Oil		Air	
Slide Span	40	inches	20	inches
Servo type[1]	1		1	
Closed loop bandwidth (-3db)	18.5	Hz	29.5	Hz
Crossover frequency	12.0	Hz	10.5	Hz
Following error at 5 IPM[2]	16	μinch	10	μinch
Least significant bit	0.1	μinch	0.1	μinch
Servo dc compliance[3]	1.1×10^{-16}	inch/lb	4.6×10^{-17}	inch/lb
Phase margin	53°		45°	
Gain margin	7.5	db	13.0	db
Static error coefficient	5,200	1/sec.	8,300	1/sec.

Velocity Loop	X-Axis		Z-Axis	
Actuator	Torque Motor/VCB		Torque Motor/VCB	
Velocity sensor	Tachometer		Tachometer	
Servo type[1]	1		1	
Closed loop bandwidth (-3db)	28.5	Hz	115	Hz
Crossover frequency	21.0	Hz	85	Hz
Phase margin	50°		50°	
Gain margin	21	db	10	db
Static error coefficient	4×10^{10}		2×10^{11}	

LODTM Fast Tool Servo Performance Characteristics

Weight moved	1.0	lb
Actuator	piezoelectric crystal	
Position sensor	differential capacitance gauge	
Span	± 100	microinches
Servo type	0	
Closed loop bandwidth (-3db)[4]	640	Hz
Crossover frequency	240	Hz
Servo dc compliance[3]	4×10^{-11}	inch/lb
Phase margin	52°	
Gain margin	5.0	db
Static error coefficient	0.5×10^{6}	

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[1] In theory, servo type is 0 due to bellows springs. In practice, the servo approximates a type 1 very closely except at dc.
[2] Measured under steady state conditions.
[3] Calculated value for dc conditions. At other frequencies compliance will be greater. This includes only the mechanical components within the slide servo loop.
[4] Measured on toolbar with X and Z slide servos operating.

TABLE 2: TOOL COORDINATE EQUATIONS

o Tool Position

$$\hat{Z} = (\hat{z}_o + a) + z_o - \left(\frac{z_1 + z_2}{2}\right) + S_1 + b\left[\phi + \frac{(x_3 + x_4) - (x_1 + x_2)}{c} + C_1\right]$$

$$X_+ = \frac{x_1 + x_3}{2} + \left(\frac{x_3 - x_1}{C}\right)(z_c - z_o)$$

$$X_- = \frac{x_2 + x_4}{2} + \left(\frac{x_4 - x_2}{C}\right)(z_c - z_o)$$

$$\hat{X} = (\hat{x}_o + b) + \frac{x_+ + x_-}{2} + S_2 + a\left[\phi + \frac{(X_3 + X_4) - (X_1 + X_2)}{2C} + C_1\right]$$

$$X = -\left(\frac{x_5 + x_6}{2}\right) + C_x + \hat{x} + \hat{z}\left[\frac{z_4 - z_3}{D} + C_\Theta\right]$$

$$Z = -\left(\frac{z_3 + z_4}{2}\right) + C_z + \hat{z} - \hat{x}\left[\frac{z_4 - z_3}{D} + C_\Theta\right]$$

o Slide Following Error

$$\epsilon_x = CNC_x - X$$

$$\epsilon_Z = CNC_Z - Z$$

o Fast Tool Servo

$$\ell = g_x \, \epsilon_x + g_z \, \epsilon_z$$

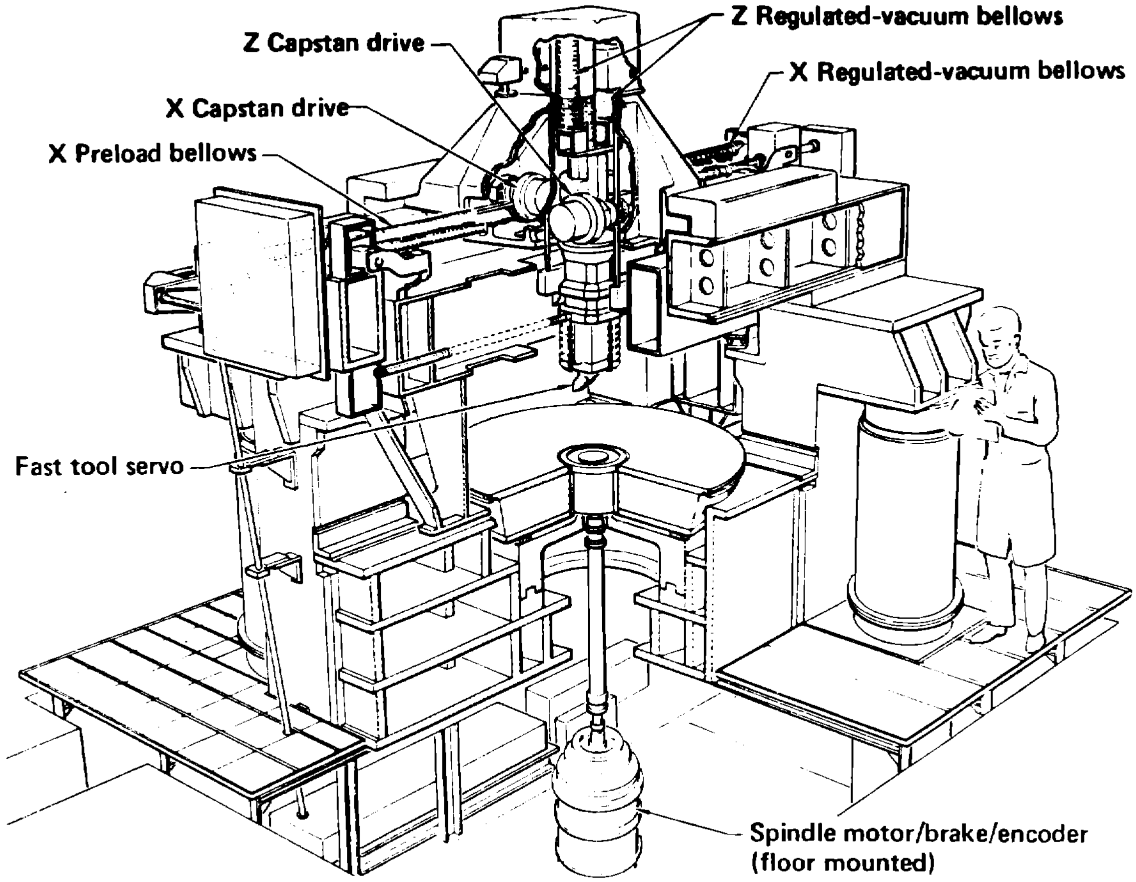

Figure 1: Large Optics Diamond Turning Machine

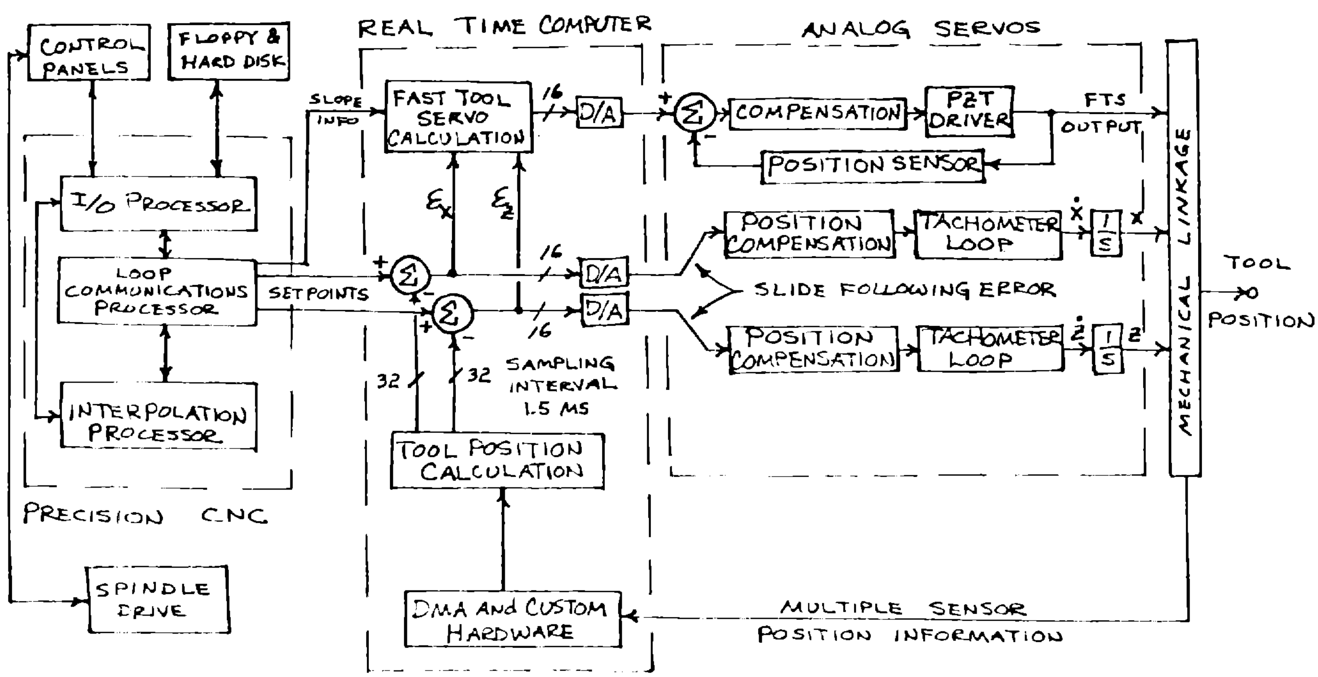

Figure 2: Simplified Motion Control Block Diagram

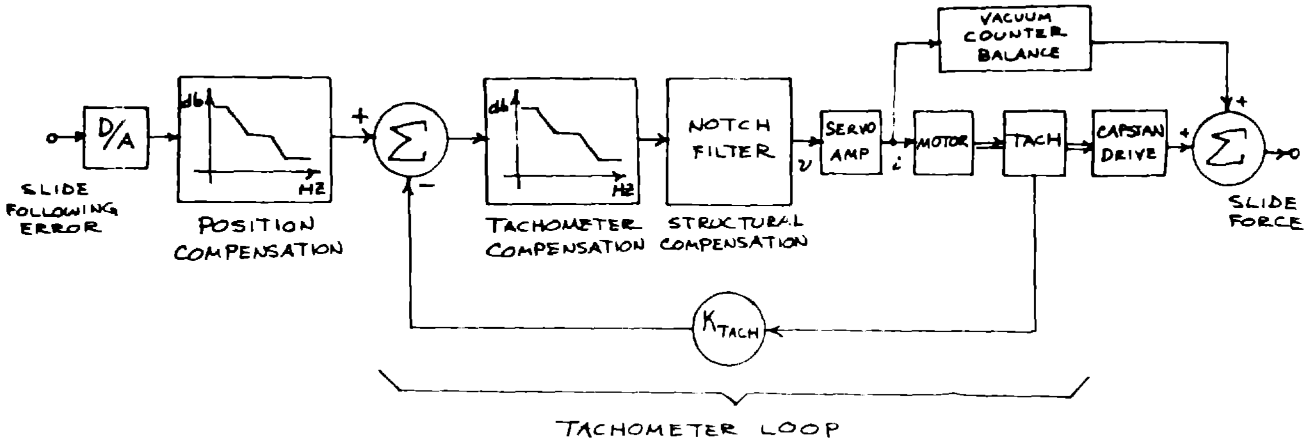

Figure 3: Slide Servo Block Diagram

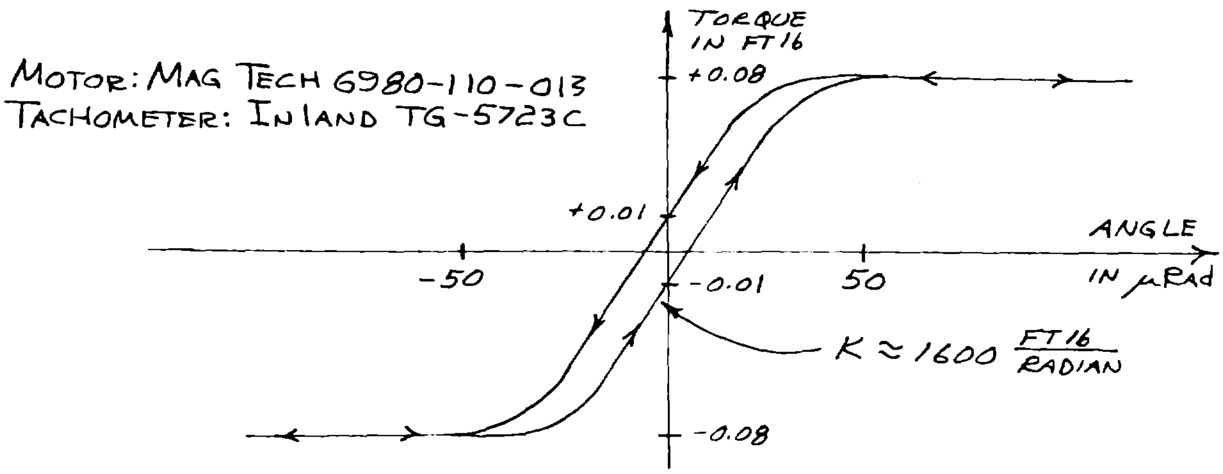

Figure 4: Motor-Tachometer Nonlinearity

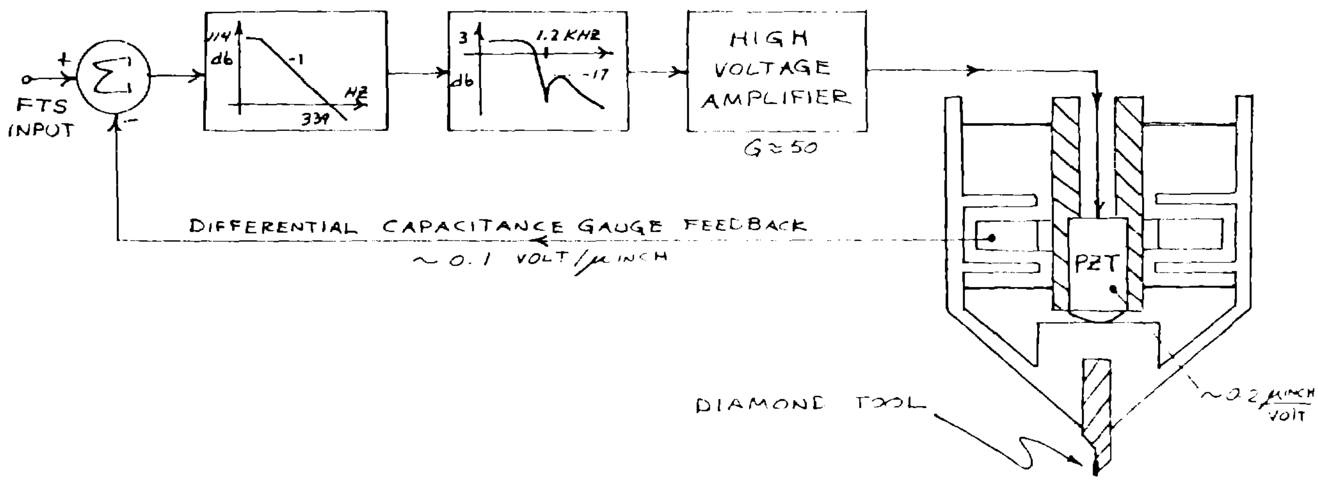

Figure 5: Fast Tool Servo Block Diagram

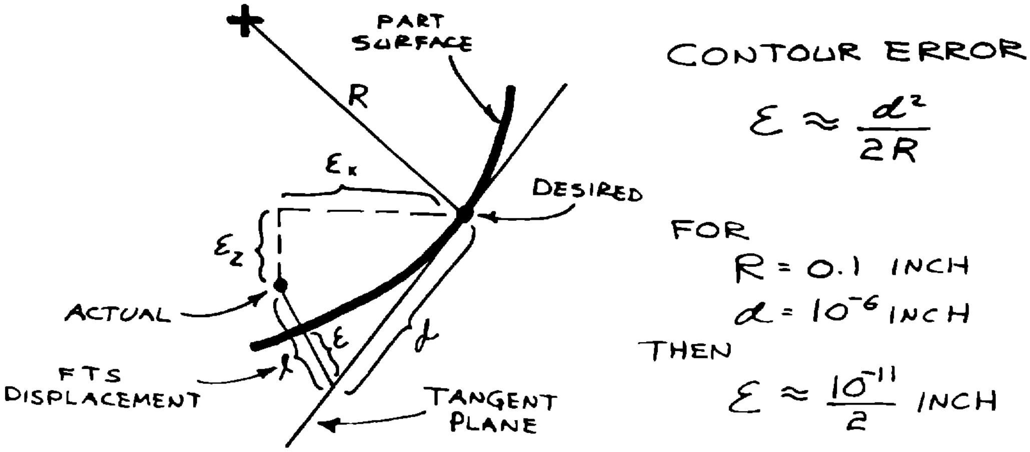

Figure 6: Single PZT Introduces a Small, Acceptable Error

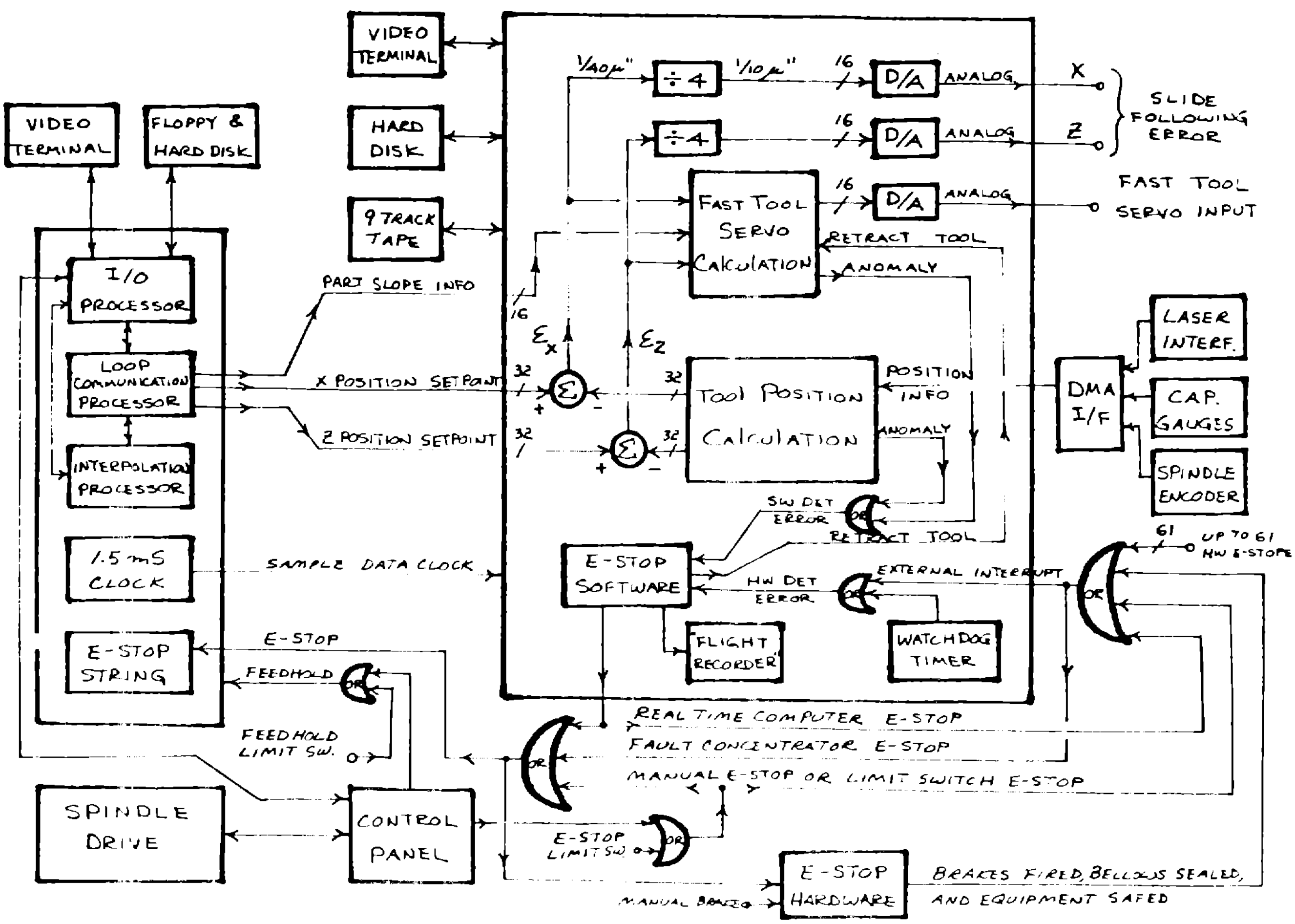

Figure 7: Functional Diagram of Real Time Computer